Numerical Investigation of the Optimal Inclination Angle of Sloped Bottom Tuned Liquid Damper

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Abstract: ***One of the most common designing issues that faces structural engineers during design phase is to ensure that the capacity of the studied structure is well enough to withstand seismic events and mitigate as mush as possible to reduce the effects of dynamic loads. This research studies the seismic behavior of sloped-bottom tuned liquid dampers (SB-TLD), these dampers will be used as motion control devices to mitigate the response building under earthquakes, an analytical model of sloped bottom TLD was built using ABAQUS^{TM} to obtain the optimum Incline angle of the sloped bottom which leads to optimum behavior of TLD, further a comparison was carried out between rectangular shaped TLD and trapezoidal shaped TLD (SBTLD). It was found that the SBTLD is more efficient and dissipates more energy than rectangular TLD.***

Keywords: Vibration mitigation, tuned liquid dampers, TLDs, sloped bottom tuned liquid dampers, SB-TLD, dynamics of liquid in containers

1. Introduction

An economical solution to reduce building motions to suitable levels, under dynamic loading, is to provide additional damping. A passive damping device shown to be effective is the tuned liquid damper (TLD). A TLD consists of a rigid tank, partially filled with a liquid, usually water. When a structure, fitted with a properly tuned TLD begins to sway during a dynamic loading event, it causes fluid sloshing motion inside the tank. The fluid sloshing motion imparts inertia forces approximately anti-phase to the dynamic forces exciting the structure, thereby reducing structural motion. The inherent damping mechanism of the TLD dissipates the energy of the fluid sloshing motion. A number of tall structures have been successfully fitted with TLD devices, resulting in a substantial reduction in structural motion [1] [2][3].

TLD has a several advantages: it works efficiently on small vibration (wind) and large ones (earthquakes), Weak possibility of collapse and failure, easy calibrated with the building and inexpensive to install and maintain, there are some drawbacks: not all the water participates in reducing the structural motion which divides the mass of water into two parts: effective mass and ineffective mass and the post excitation motion in TLD which leads to return some of the energy gained by TLD to the building which negatively affects it.

[4]studied effective TLD parameters including liquid height, Mass, frequency, and damping for a TLD attached to offshore platforms. [5]was among the first researchers who applied TLDs to ground civil engineering structures by introducing a rectangular tank full of two immiscible liquids to decrease structural vibration. [6]presented a numerical model to solve for Navier-Stokes and continuity equation based on shallow water wave theory. They discretized the main equations and solved them numerically. [7]suggested a nonlinear model that utilizes the shallow water wave theory and solves Navier-Stokes and continuity equations together. Furthermore, they introduced two empirical coefficients to account for the effect of wave breaking which is a significant deficiency in many other models. [8]investigated the effect of different tank shapes of TLD in energy dissipation and they found that the trapezoidal shape was the most efficient between rectangular, conical and inverse trapezoidal tanks, [9]investigated the performance of a sloped-bottom TLD with an angle of 30° to the tank base. It is shown that despite the hardening spring behavior of a rectangular TLD, the sloped-bottom TLD behaves as a softening spring. Also, it is observed that more liquid mass participates in sloshing force in the slopped-bottom case leading to more energy dissipation. [10]presented a nonlinear modal of TLD under forced pitching oscillation to solve Navier-Stokes and continuity equations and they found a very good match between their results and experimental ones.

2. Frequency Equations

Formulation of the natural frequency which used in the models and the assumptions to simplify the problems are discussed in this section. For rectangular tank, the continuity equations can be written for incompressible, inviscid and irrotational fluid as [11]:

$$\frac{\partial^2 \Phi}{\partial x^2}+\frac{\partial^2 \Phi}{\partial y^2}+\frac{\partial^2 \Phi}{\partial z^2}=0 \;\Longrightarrow\; \nabla^2\Phi=0 \qquad (1)$$

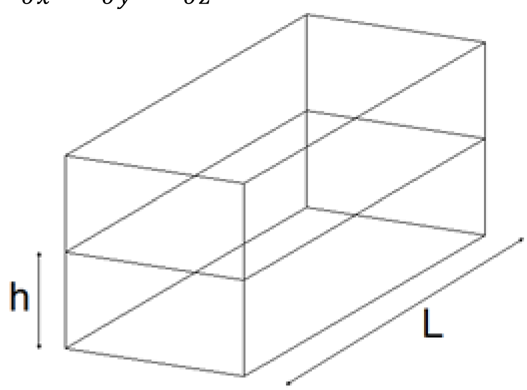

Figure 1: Geometry of rectangular TLD (L: dimension in excitation direction, h: mean water elevation).

Where x, y, z are components of Cartesian coordinate and Φ is velocity potential functioin. Geometry of the cubic tank is illustrated in Fig. 1. The free surface boundary condition can be expressed as:

$$\frac{\partial \Phi(x,y,z,t)}{\partial t} + g\delta(x,y,t) = \frac{-P_o}{\rho} \quad (2)$$

Where ρ is density, $\delta(x,y,t)$ is the small displacement of the free surface above the undisturbed Level and 0, p is the static pressure of the gas above the liquid. The difference between $z = h$ and $z = h + \delta$ turns out to be a higher order term in and so can be neglected. The relation of the surface displacement δ to the vertical component of the liquid velocity at the surface is:

$$\frac{\partial \delta}{\partial t} = w = \frac{\partial \Phi}{\partial z} \; ; z = h \quad (3)$$

Introducing Eqn. 3 into Eqn. 2 gives:

$$\frac{\partial^2 \Phi}{\partial t^2} + g.\frac{\partial \Phi}{\partial z} = 0 \quad ; z = h \quad (4)$$

According to [12]two forms of possible potential functions are:

$$\varphi_1(x,z) = F.\cos\left(2n\pi\frac{x}{l}\right)\left\{\cosh\left(2n\pi\frac{z}{l}\right) + \tanh\left(2n\pi\frac{h}{l}\right)\sinh\left(2n\pi\frac{z}{l}\right)\right\} \quad (5-1)$$

$$\varphi_2(x,z) = G.\cos\left((2n-1)\pi\frac{x}{l}\right)\left\{\cosh\left((2n-1)\pi\frac{z}{l}\right) + \tanh\left((2n-1)\pi\frac{h}{l}\right)\sinh\left((2n-1)\pi\frac{z}{l}\right)\right\} \quad (5-2)$$

Applying the boundary conditions and substituting the proposed solution, Eqn. 5, into the free surface boundary condition, Eqn. 2 gives the natural frequency in the form of [12] [5]:

$$\omega^2 = n\pi\frac{g}{l}\tanh\left(n\pi\frac{h}{l}\right) \quad (6)$$

For SB-TLD [13] Developed a method to calculate natural frequency by substituting l in eqn.6 with L1 (wet parameter) which can be calculated by eqn.7:

$$L_1 = L_o + \frac{2h}{\sin\theta} \quad (7)$$

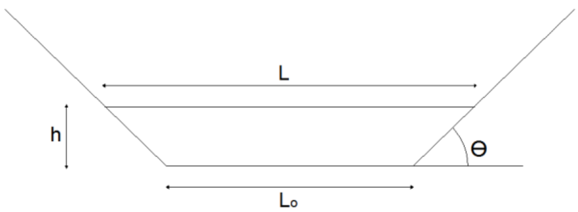

Figure 2: Geometry of SB-TLD

3. Numerical Modals

TLDs are numerically modelled using ABAQUS™ software and the models consist of two parts. The first part is employed to model water, the TLD tank is modelled by the second part. CPE3 and R2D2 elements are used to model the water and the rigid tank, respectively [14].

Gravity loading is defined for the water and the water is considered incompressible and inviscid.Frictionless contact is defined between water and tank.Furthermore, the linear equation of state is employed with a wave speed of 45 m/s and density of 983.2 kg/m3. Also, adaptive meshing option of ABAQUS™ is used in this model.

Figure 3 shows the Modeled rectangular TLD with dimensions: L=0.9 m, h=0.6 m subjected to forced pitching oscillation:

$$\theta = 0.01396\ \cos(5.5t) \quad (8)$$

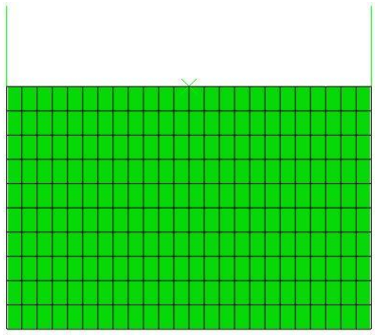

Figure 3: Rectangular TLD Model.

Figure 4 shows water motion at different time increments:

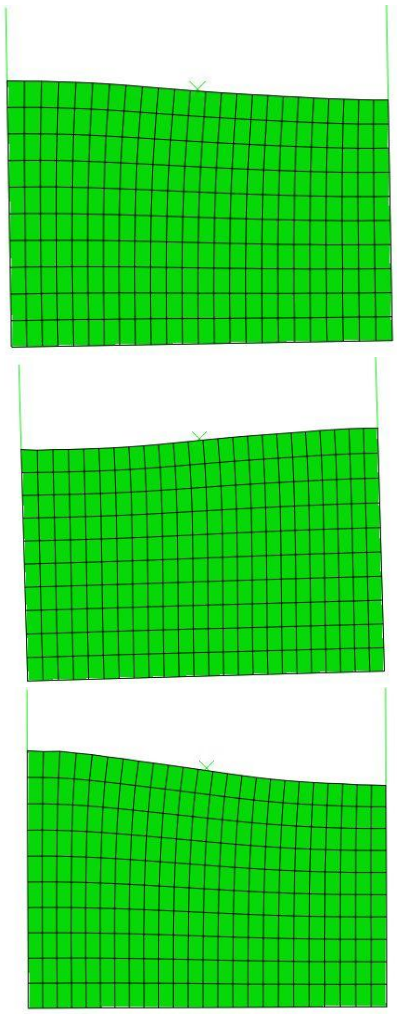

Figure 4: Water motion inside TLD at: 4.9 - 6.3 - 7 sec respectively

Figure 5 shows a comparison between modal results and [10]results:

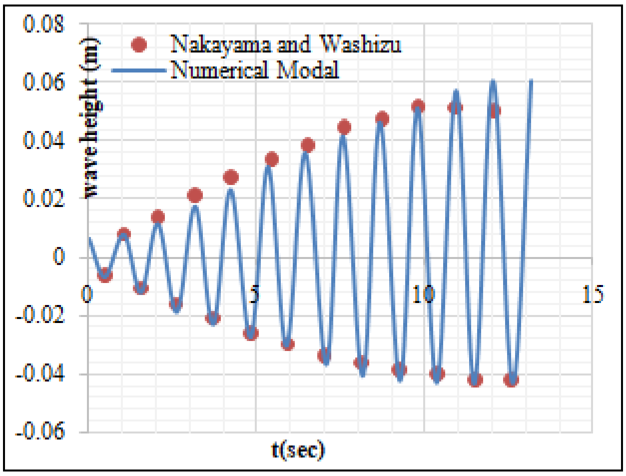

Figure 5: Wave height vs. time according to modal results and [10] results.

Figure 6 shows SB-TLD Model with its dimensions subjected to forced pitching oscillation:

$$\theta = 0.1 * \cos(1.66t) \quad (9)$$

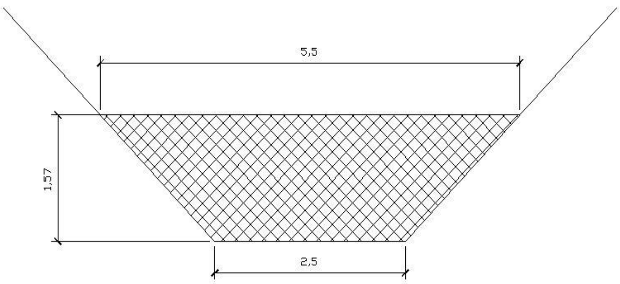

Figure 6: SB-TLD Model Geometry

Figure 7 shows water motion at different time increments:

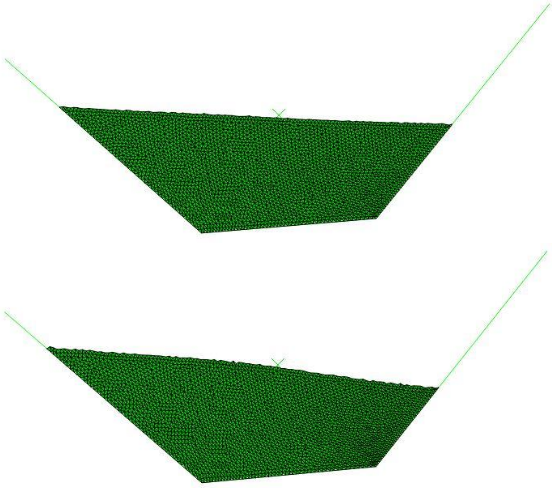

Figure 7: Water motion inside SB-TLD at: 4.2 - 6 sec respectively

To validate the model, a comparison between modal results and [8]results was shown in figure 8:

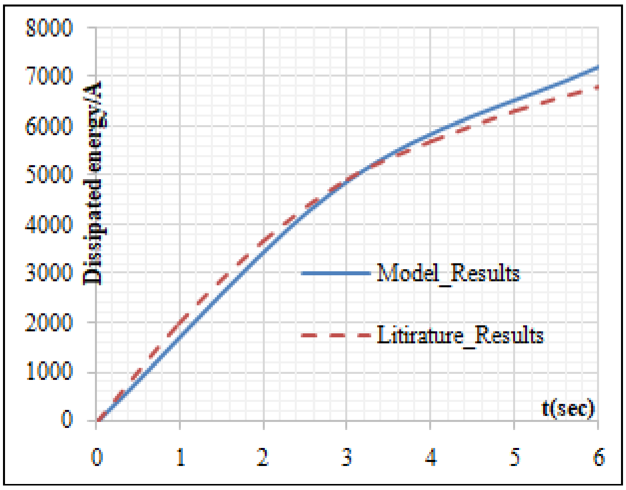

Figure 8: Dissipated energy per Mass unite vs. time according to SB-TLD Modal and [8].

Figures 5 and 8 show that there is a good match between modals results and results obtained by [10]and [8]which validates the modals.

4. Comparison between rectangular TLD and sloped bottom TLD:

A comparison between rectangular TLD and SB-TLD (that had the same natural frequency) has been done based on their ability to dissipate energy and reducing post excitation motion which occurs in TLD.

The rectangular TLD with a dimension of: L=6.74m, H=1.5 m and a SB-TLD with dimensions showed in figure 6 were used. Both TLDs are subjected to forced pitching oscillation given by eqn.10:

$$\theta = 0.1 * \cos(1.66t) \quad (10)$$

Figure 9 demonstrates the amount of dissipated energy per mass unite for each TLD:

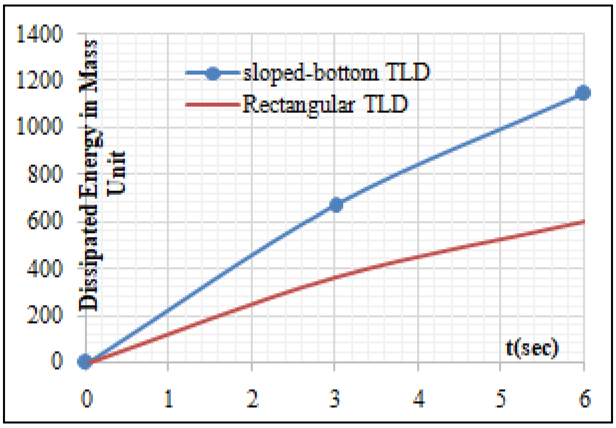

Figure 9: Dissipated energy per mass unite vs. time for SB-TLD and rectangular TLD.

It's clear from previous figure that the SB-TLD dissipates more energy than rectangular TLD which indicates that the SB-TLD is more efficientthan rectangular TLD and has more effective mass than the latter one.

5. The Optimum Incline Angle of SB-TLD:

In this section three SB-TLD with Dimensions:
L=4.2 m, Lo =0.95 m, h=0.6 m, θ=20o.
L=5.11 m, Lo =1.65 m, h=1 m, θ=30o.
L=5.5 m, Lo =2.5 m, h=1.57 m, θ=45o.

All SB-TLD have the same natural frequency and subjected to excitation by eqn.11:

$$\theta = 0.1 * \cos(1.66t) \qquad (11)$$

Figure 10 illustrates the amount of dissipated energy vs. time for all SB-TLDs:

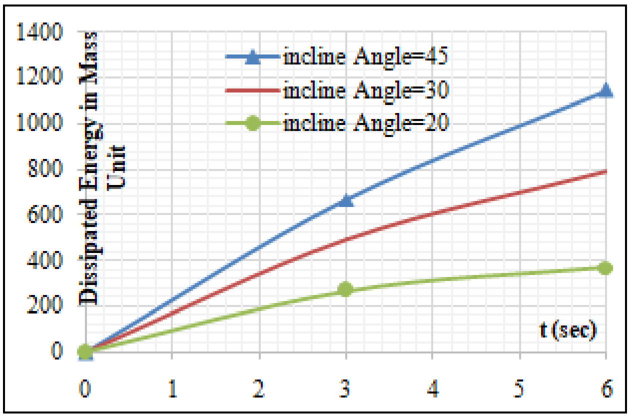

Figure 10: Dissipated energy per Mass unite vs. time for different inclination angle.

The SB-TLD with incline angle equals to 45 degrees has the best performance because of its ability to dissipate more energy than other TLDs.

6. Sun et al (1992) TLD Model:

[7]introduced a model to solve nonlinear Navier-Stokes and Continuity equations. A combination of boundary layer theory and shallow Water wave theory is employed and resulting equations were solved using Numerical methods. An important aspect of this model is that it considers Wave breaking under large excitations by means of two empirical Coefficients.

A single degree of freedom system (SDOF) with TLD is considered as shown in figure 11, the whole system is subjected to harmonic excitation demonstrated in eqn.12:

$$P = 3000 * \sin(2\pi f_s t) \qquad (12)$$

Where: f_s: SDOF frequency.

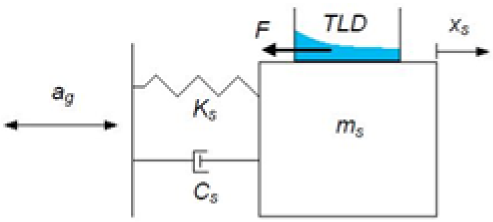

Figure 11: Schematic of SDOF with TLD combined.

SDOF has a mass of 56400 Kg, stiffness of 242470 N/m and damping of 945 N.sec/m. By Applying equation of [7] to whole system and using MATLab^{TM} to solve the equations and obtain the results shown in figures 12-13-14-15 as follows:

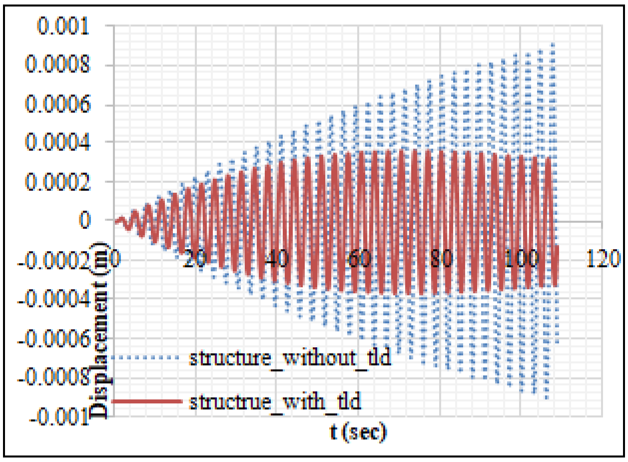

Figure 12: Displacement vs. time for SB-TLD with incline angle equals 20°

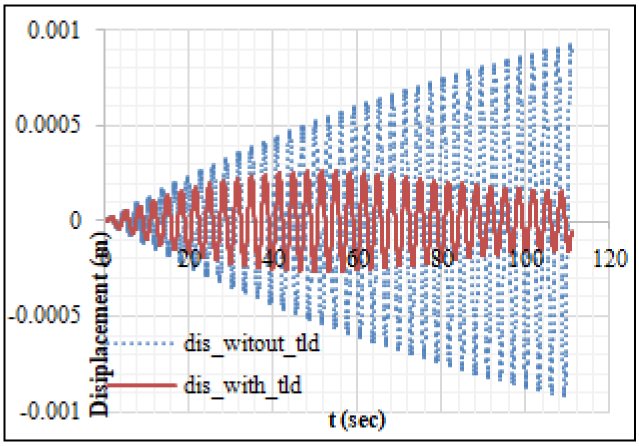

Figure 13: Displacement vs. time for SB-TLD with incline angle equals 30°

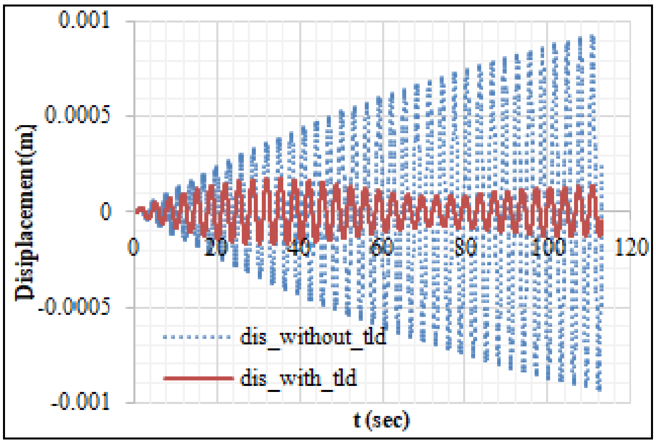

Figure 14: Displacement vs. time for SB-TLD with incline angle equals 45°.

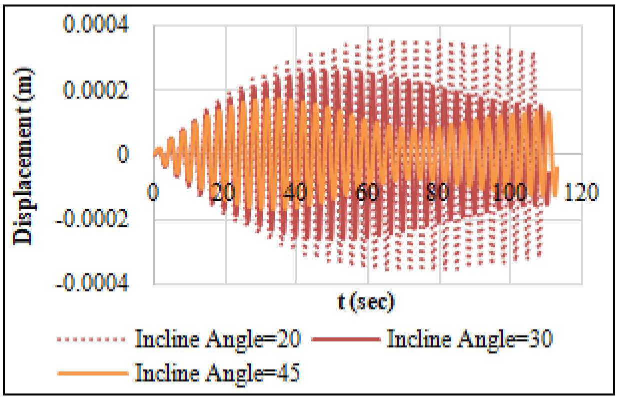

Figure 15: Displacement vs. time for SB-TLDs with incline angles equals to :(20°, 30°, 45°)

It can be concluded from figures 12 to 15 that the SB-TLD with incline angle equals to 45 degree is the most efficient, this conclusion emphasizes the former one in this paper. However, It can be noticed that the performance of SB-TLD reaches an optimum point and then becomes less efficient and so on, this can be explained due to the nature of water motion; when there is more water waves is anti-phase to SDOF motion the SB-TLD gets more efficient, it becomes less efficient when less water waves participates in inertial force anti-phase to SDOF motion.

7. Conclusions

In this paper, a computational model was built using FEM software to capture the behavior of TLDs both rectangular and sloped bottom by measuring the ability of both TLDs to dissipate energy and to mitigate vibration. Depending on the results of the numerical investigations, SB-TLD dissipates more energy than rectangular TLD which indicates that SB-TLD has more effective mass than normal one because of the circulation zones that occurs in rectangular TLDs due to water motion which makes it less efficient and decrease effective mass. Also, SB-TLD reduces post excitation motion more efficiently than rectangular TLD.

The optimum angle of inclination in SB-TLD was found to be equal to 45 degrees because SB-TLD with incline angle equals to 45 dissipates energy the most and mitigates the vibrations when subjected to harmonic excitation.

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Author Profile

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